

**METHOD OF DEPOSITING AMORPHOUS SILICON BASED  
FILMS HAVING CONTROLLED CONDUCTIVITY**

CROSS REFERENCE TO RELATED APPLICATIONS

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This application is a continuation-in-part of U.S. Application Serial No. 08/500,728, filed July 11, 1995, and entitled "Method of Depositing Amorphous Silicon Based Films Having Controlled Conductivity," which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

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The present invention generally relates to a method of depositing on a substrate an amorphous silicon based film that has controlled electrical conductivity and more particularly, relates to a method of depositing an amorphous silicon based film that has controlled conductivity in between that of an intrinsic amorphous silicon and an n<sup>+</sup> doped amorphous silicon. The film may be deposited onto a substrate by a chemical vapor deposition process. In recent years, flat panel display devices have been developed for use in many electronic applications including notebook computers. One such device, an active matrix liquid crystal display, has been used frequently. However, the liquid crystal display device has inherent limitations that render it unsuitable for many applications. For instance, liquid crystal displays have fabrication limitations such as a slow deposition process of amorphous silicon on glass, high manufacturing complexity and low yield. The displays require a power-hungry fluorescent backlight while most of the light is wasted. A liquid crystal display image is also difficult to see in bright sunlight or at extreme viewing angles which present a major concern in many applications.

A more recently developed device of a field emission display (FED) overcomes some of these limitations and provides significant benefits over the liquid crystal display devices. For instance, the FEDs have higher contrast ratio, larger viewing angle, higher maximum brightness, lower power consumption and a wider operating temperature range when compared to a typical thin film transistor liquid crystal display device.

Unlike the liquid crystal displays, field emission displays (FEDs) produce

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their own light using colored phosphors. The FEDs do not require complicated, power-consuming backlights and filters and almost all the light generated by an FED is visible to the user. The FEDs do not require large arrays of thin-film transistors. A major source of yield problems for active matrix liquid crystal displays is therefore eliminated.

In a FED, electrons are emitted from a cathode and impinge on phosphors on the back of a transparent face plate to produce an image. It is known that such a cathodoluminescent process is one of the most efficient ways for generating light. Unlike a conventional CRT, each pixel in an FED has its own electron source, typically an array of emitting microtips. The voltage difference between the cathode and the gate extracts electrons from the cathode and accelerates them towards the phosphors. The emission current and thus the display brightness, is strongly dependent on the work function of the emitting material. The cleanliness and uniformity of the emitter source material are therefore essential.

Most FEDs are evacuated to low pressures, i.e.,  $10^{-7}$  torr, to provide a long mean free path for emitted electrons and to prevent contamination and deterioration of the tips. Display resolution is improved by using a focus grid to collimate the electrons drawn from the microtips.

The first field emission cathodes developed for a display device used a metal microtip emitter of molybdenum. In such a device, a silicon wafer is first oxidized to produce a thick  $\text{SiO}_2$  layer and then a metallic gate layer is deposited on top of the oxide. The gate layer is then patterned to form gate holes. Etching the  $\text{SiO}_2$  underneath the holes undercuts the gate and creates a well. Molybdenum is deposited at normal incidence and, at the same time, a sacrificial material such as Ni is deposited from a source placed at the side of the device such that cones with sharp points grow inside the cavities. Emitter cones are left when the sacrificial layer is removed.

In another FED device, silicon microtip emitters are produced by thermally oxidizing a silicon substrate, patterning the silicon oxide to expose the underlying silicon substrate, and selectively etching the exposed silicon to form silicon tips. Further oxidation and etching protects the silicon and sharpens the points of the silicon tips.

In an alternative design, the microtips are added onto a substrate of desired materials such as glass, which is an ideal substrate material for large area flat panel display. The microtips can be made of conducting materials such as metals or doped semiconductors. In such a FED device, an interlayer with controlled conductivity between the cathode and the microtips is highly desirable. Proper engineering of the resistivity of the interlayer enables the device to operate in a stable and controllable fashion. The resistivity of the interlayer is in the order between an insulator and a conductor, while the actual desired value depends on the specifics of the device design.

Chemical vapor deposition (CVD) or plasma-enhanced chemical vapor deposition (PECVD) are processes widely used in the manufacture of semiconductor devices for depositing layers of materials on various substrates. In a conventional PECVD process, a substrate is placed in a vacuum deposition chamber equipped with a pair of parallel plate electrodes. The substrate is generally mounted on a susceptor which is also the lower electrode. A reactant gas flows into the deposition chamber through a gas inlet manifold which also serves as the upper electrode. A radio frequency (RF) voltage is applied between the two electrodes which generates an RF power sufficient to cause a plasma to be formed in the reactant gas. The plasma causes the reactant gas to decompose and deposit a layer of the desired material on the surface of the substrate body. Additional layers of other electronic materials can be deposited on the first layer by flowing into the deposition chamber a reactant gas containing the material of the additional layer to be deposited. Each reactant gas is subjected to a plasma which results in the deposition of a layer of the desired material.

In the fabrication of a field emission display device, it is desirable to deposit an amorphous silicon based film that has electrical conductivity in an intermediate range between that of intrinsic amorphous silicon and  $n^+$  doped amorphous silicon. The conductivity of the  $n^+$  doped amorphous silicon is controlled by adjusting the amount of phosphorus atoms contained in the film. Even though it is possible, in principle, to produce an intermediate conductivity film by adding very small amounts of phosphorus atoms, it is a very difficult task, i.e. requires specially premixed

PH<sub>3</sub>/H<sub>2</sub> to precisely control the amounts of the phosphorus atoms.

Since field emitting display devices use very thick layers, it becomes necessary to deposit low stress films to prevent warping of the glass and peeling of the films. The standard process for depositing amorphous silicon produces films that are highly compressive, especially when deposited at high deposition rates.

### SUMMARY OF THE INVENTION

The present invention provides a deposition method for preparing amorphous silicon based films with controlled resistivity and low stress. Such films can be used as the interlayer in the FED manufacturing. They can also be used in other electronic devices which require films with controlled resistivity in the range between those of an insulator and of a conductor. The deposition method described in the present invention employs the method of chemical vapor deposition or plasma-enhanced chemical vapor deposition; other film deposition techniques, such as physical vapor deposition, also may be used.

In one aspect, the invention features a method of forming an amorphous silicon-based film on a substrate located inside a deposition chamber, comprising: introducing a silicon-based volatile into the deposition chamber; introducing into the deposition chamber a conductivity-increasing volatile comprising one or more components for increasing the conductivity of the amorphous silicon-based film; and introducing into the deposition chamber a conductivity-decreasing volatile comprising one or more components for decreasing the conductivity of the amorphous silicon-based film.

In another aspect, the invention features a method of forming an amorphous silicon-based film on a substrate located inside a deposition chamber, comprising: introducing a silicon-based volatile into the deposition chamber; introducing phosphine into the deposition chamber; and introducing a nitrogen-containing volatile into the deposition chamber.

In yet another aspect, the invention features a method of forming an amorphous silicon-based film on a substrate located inside a deposition chamber, comprising: introducing a silicon-based volatile into the deposition chamber; introducing phosphine into the deposition chamber; and introducing a carbon-

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containing volatile into the deposition chamber.

Embodiments may include one or more of the following features.

The conductivity-increasing volatile and the conductivity-decreasing volatile may be introduced into the deposition at respective relative flow rates selected to achieve a desired film resistivity. The relative flow rates may be selected to achieve a film resistivity of about  $10^3$ - $10^7$  ohm-cm. The conductivity-increasing volatile may consist of phosphine and the conductivity-decreasing volatile may consist of ammonia, the phosphine and the ammonia being introduced into the deposition chamber at a flow rate ratio in a range of about 1:1000 to about 1:10 (phosphine:ammonia). Alternatively, the conductivity-increasing volatile may consist of phosphine and the conductivity-decreasing volatile may consist of methane, the phosphine and the methane being introduced into the deposition chamber at a flow rate ratio in a range of about 1:100 to about 1:1 (phosphine:methane).

The conductivity-increasing volatile may comprise a dopant. The dopant may comprise an n-type dopant (e.g., phosphorous) or a p-type dopant (e.g., boron).

The amorphous silicon-based film may be characterized by a band gap, and the conductivity-decreasing volatile preferably comprises a band gap increasing component that increases the band gap of the amorphous silicon-based film relative to a film formed under similar conditions but without the band gap increasing component. The conductivity-decreasing volatile may comprises nitrogen, ammonia,  $N_2$ ,  $N_2O$ , carbon (e.g., methane)

In one embodiment, the silicon-based film consists of silane, the conductivity-increasing volatile consists of phosphine, and the conductivity-decreasing volatile consists of ammonia. In another embodiment, the silicon-based film consists of silane, the conductivity-increasing volatile consists of phosphine, and the conductivity-decreasing volatile consists of methane. In yet another embodiment, the silicon-based film consists of silane, the conductivity-increasing volatile consists of phosphine, the first conductivity-decreasing volatile consists of ammonia, and the second conductivity-decreasing volatile consists of methane.

A second conductivity-decreasing volatile may be introduced into the deposition chamber.

In a preferred embodiment, amorphous silicon based films of precisely

controlled electrical conductivity and low stress are produced by flowing a reactant gas mixture into a plasma-enhanced chemical vapor deposition chamber. The reactant gas mixture comprises silane, ammonia and phosphine carried by a hydrogen gas. Changing the phosphorus content by controlling the phosphine partial pressure, the n-type electrical conductivity of the amorphous silicon based film can be changed, i.e. increasing the phosphorus content increases the electrical conductivity. Changing the nitrogen content of the reactant gas by controlling the ammonia partial pressure, the resistivity can be changed, i.e. increasing the nitrogen content increases the resistivity of the amorphous silicon based film. An ideal range of resistivity for the field emission display devices is between about  $10^3$  and about  $10^7$  ohm-cm. The novel method described in this invention enables one to control the resistivity of an amorphous silicon based film within the desirable range of  $10^3$  to  $10^7$  ohm-cm. The films produced by the novel method have low tensile stress such that warping or peeling of films from substrates are avoided.

The present invention is also directed to a field emission display device fabricated by a plasma-enhanced chemical vapor deposition technique in which a reactant gas mixture comprising silane, hydrogen, phosphine (carried in hydrogen) and ammonia is used to produce an amorphous silicon based film having controlled electrical conductivity. By adjusting the flow rate of each component gas, an amorphous silicon based film having a precisely controlled electrical conductivity and low stress for forming a field emission device can be obtained.

Among the advantages of the invention are the following.

The invention provides a method of depositing amorphous silicon based films that have controlled conductivity and low stress in a chemical vapor deposition process or a plasma-enhanced chemical vapor deposition process by incorporating simple process control steps. The invention also provides a method of depositing amorphous silicon based films that have controlled conductivity and low stress in a chemical vapor deposition process or a plasma-enhanced chemical vapor deposition process by using a reactant gas mixture containing  $\text{PH}_3$  and  $\text{NH}_3$ . The present further provides a method of depositing amorphous silicon based films that have controlled conductivity and low stress in a chemical vapor deposition process or a plasma enhanced chemical vapor deposition process by controlling the

flow rates of the reactant gases in the reaction chamber.

Other features and advantages will become apparent from the following description, including the drawings and the claims.

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#### BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic sectional view of a plasma-enhanced chemical vapor deposition chamber in which the method in accordance with the present invention can be carried out.

10 Figure 2 is an enlarged cross-sectional view of a typical field emission display device.

Figure 3 is a graph illustrating the dependence of resistivity on the flow rate ratio between  $\text{PH}_3$  and  $\text{NH}_3$ .

Figure 4 is a graph illustrating the dependence of stress on the flow rate ratio between  $\text{PH}_3$  and  $\text{NH}_3$ .

15 Figure 5 is a graph of the resistivity of amorphous silicon-based films plotted against the flow rate ratio phosphine:methane.

#### DETAILED DESCRIPTION

20 The present invention discloses an improved method of depositing amorphous silicon based films having controlled electrical conductivity and low stress on a substrate for an electronic device, such as a field emission display device by a plasma enhanced chemical vapor deposition technique.

Referring initially to Figure 1, there is shown a schematic sectional view of a plasma-enhanced chemical vapor deposition apparatus 10 in which the method in accordance with the present invention can be carried out. Turner et al. disclose such an apparatus in U.S. Patent No. 5,512,320. A deposition chamber 12 includes an opening through a top wall 14 and a first electrode or a gas inlet manifold 16 within the opening. Alternatively, the top wall 14 can be solid with the electrode 16 being adjacent to the inner surface thereof. Within chamber 12 is a susceptor 18 in the form of a plate which extends parallel to the first electrode 16. The susceptor 18 is typically of aluminum and is coated with a layer of aluminum oxide. The susceptor 18 is connected to ground so that it serves as a second

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electrode so as to connect the RF source 36 across the two electrodes 16 and 18.

The susceptor 18 is mounted on the end of a shaft 20 which extends vertically through a bottom wall 22 of the deposition chamber 12. The shaft 20 is movable vertically so as to permit the movement of the susceptor 18 vertically toward and away from the first electrode 16. A lift-off plate 24 extends horizontally between the susceptor 18 and the bottom wall 22 of the deposition chamber 12 substantially parallel to the susceptor 18 and is vertically movable. Lift-off pins 26 project vertically upwardly from the lift-off plate 24. The lift-off pins 26 are positioned to be able to extend through lift holes 28 in the susceptor 18, and are of a length slightly longer than the thickness of the susceptor 18. While there are only two lift-off pins 26 shown in the figure, there may be more lift-off pins 26 spaced around the lift-off plate 24.

A gas outlet 30 extends through a side wall 32 of the deposition chamber 12 and is connected to means (not shown) for evacuating the deposition chamber 12. A gas inlet pipe 42 extends into the first electrode or the gas inlet manifold 16 of the deposition chamber 12, and is connected through a gas switching network (not shown) to sources (not shown) of various gases. The first electrode 16 is connected to an RF power source 36. A transfer paddle (not shown) is typically provided to carry substrates through a load-lock door (not shown) into the deposition chamber 12 and onto the susceptor 18, and also to remove the coated substrate from the deposition chamber 12.

In the operation of the deposition apparatus 10, a substrate 38 is first loaded into the deposition chamber 12 and is placed on the susceptor 18 by the transfer paddle (not shown). The substrate 38 is of a size to extend over the lift holes 28 in the susceptor 18. A commonly used size for a flat panel display device substrate is approximately 360 mm by 465 mm. The susceptor 18 is positioned above the lift-off pins 26 by moving shaft 20 upwards such that the lift-off pins 26 do not extend through the holes 28, and the susceptor 18 and substrate 38 are relatively close to the first electrode 16. The electrode spacing or the distance between the substrate surface and the discharge surface of the gas inlet manifold 16 is between about 12 to about 50 mm. A more preferred electrode spacing is between about 20 to about 36 mm.

FIG. 10



Before the deposition process of the invention, the substrate 38, which may be a large sheet of a transparent material, is processed according to well known techniques. After the initial processing in the preferred embodiment, a top most layer containing a patterned metal is deposited.

At the start of the deposition process of the invention, the deposition chamber 12 is first evacuated through the gas outlet 30. The patterned substrate 38 is then positioned on the susceptor 18. The substrate 38 is kept at a temperature between about 200°C and about 400°C during deposition of the present invention amorphous silicon film. A preferred temperature range for the substrate is between about 300°C and about 350°C during deposition. A pressure is maintained in the reaction chamber during deposition at between about 0.5 torr and about 5 torr, a preferred pressure range is between about 1.5 torr and about 2.5 torr. A detailed description of processing with this apparatus is contained in U.S. Patent 5,399,387 Law et al. assigned to the common assignee which is hereby incorporated by reference in its entirety.

Figure 2 shows an enlarged cross-sectional view of a typical field emission display device 50. The device 50 is formed by depositing a resistive layer 52 of amorphous silicon based film on a glass substrate 54. An insulator layer 56 and a metallic gate layer 58 are then sequentially formed and etched in such a way as to form metallic microtips 60. A cathode structure 60 is covered by the resistive layer 52. Thus, a resistive but somewhat conductive amorphous silicon layer 52 underlies a highly insulating layer 56, such as of SiO<sub>2</sub>. It is important to be able to control the resistivity of the amorphous silicon layer 52 so that it is not overly resistive but it will act as a limiting resistor to prevent excessive current flow if one of the microtips 60 shorts to the metal layer 58.

It should be noted that while a field emission display device is shown here to demonstrate the present invention method, the method is by no means limited to the fabrication of FEDs. The present invention method can be used in the fabrication of any electronic devices that require a deposition of a layer having controlled resistivity.

A series of tests were conducted on test samples prepared by the present invention method to determine the effects of the reactant flow rates upon the

conductivity and the stress of the films produced. Their results are summarized in Tables 1 and 2.

#### Example 1

Example 1 illustrates a deposition process for an intrinsic amorphous silicon film that does not contain doping gases in the reactant gas mixture. The film is formed as a byproduct of a reaction of silane and hydrogen in a plasma on a heated substrate. The flow rate of silane is controlled at 1,000 sccm, the flow rate of hydrogen is controlled at 1,000 sccm, the plasma power (i.e. RF power supplied to electrode 16) used is 300 W, the pressure of the chamber is kept at 2.0 torr, the electrode spacing (i.e., the spacing between electrode 16 and susceptor 18) is kept at 962 mils (2.44 cm), the susceptor, which heats the substrate by contact heating, is maintained at a temperature of 410°C, and the deposition rate obtained is 168 nm/min. After the completion of the deposition process, the films obtained were tested to produce the following physical properties, a compressive stress of  $8.0 \times 10^8$  dyne/cm<sup>2</sup> and a resistivity of  $2.0 \times 10^9$  ohm-cm.

#### Example 2

Example 2 illustrates a deposition process for p-doped amorphous silicon wherein the film was deposited with a flow of PH<sub>3</sub> gas but with no NH<sub>3</sub> gas. The flow rate of silane is 1,000 sccm, the flow rate of PH<sub>3</sub> is 0.5 sccm, the flow rate of hydrogen is 1,000 sccm, the RF power used is 300 W, the pressure of the chamber is 2.0 torr, the susceptor spacing is 962 mils (2.44 cm), the susceptor temperature is 410°C, and the deposition rate achieved is 156 nm/min. The phosphine is a 0.5% concentration in a hydrogen carrier that is otherwise accounted for in the cited flow rates. The amorphous silicon film obtained has a compressive stress of  $1.7 \times 10^9$  dyne/cm<sup>2</sup> and a resistivity of  $1.7 \times 10^2$  ohm-cm.

#### Example 3

In this example, only ammonia gas and not PH<sub>3</sub> gas is used in the reactant gas mixture. The flow rate of silane gas used is 1,000 sccm, the flow rate of NH<sub>3</sub> is 500 sccm, the flow rate of hydrogen gas is 1,000 sccm, the RF power used is

300 W, the pressure of the chamber is kept at 2.0 torr, the electrode spacing is 962 mils (2.44 cm), the temperature of the susceptor is 410°C, and a deposition rate of 135 nm/min was obtained. The physical properties obtained for the film are quite different than that obtained in Example 2. The stress of the film is in a tensile mode of  $7.4 \times 10^9$  dyne/cm<sup>2</sup>. The resistivity of the film measured has a high value of  $2.2 \times 10^{10}$  ohm-cm.

#### Example 4

In this example, a doping gas of PH<sub>3</sub> and a nitrogen-containing gas of NH<sub>3</sub> are used in the reactant gas mixture. The flow rate ratio of PH<sub>3</sub> to NH<sub>3</sub> is  $1.25 \times 10^{-2}$  to 1. The flow rate of silane is 1,000 sccm, the flow rate of PH<sub>3</sub> is 2.5 sccm, the flow rate of NH<sub>3</sub> is 200 sccm, the flow rate of H<sub>2</sub> is 1,000 sccm. The RF power used is 600 W, the pressure of the chamber is 2.0 torr, the spacing of the electrodes is 962 mils (2.44 cm), the susceptor temperature is 400°C, and the deposition rate obtained is 197 nm/min. An amorphous silicon film having a desirable resistivity is obtained. The physical properties of the film are measured at a tensile stress of  $4.0 \times 10^8$  dyne/cm<sup>2</sup> and a resistivity of  $1.6 \times 10^5$  ohm-cm. It is noted that the resistivity value is about halfway between the two extreme values shown in Example 2 and Example 3, i.e.  $1.7 \times 10^2$  and  $2.2 \times 10^{10}$ .

#### Example 5

In this example, both gases of PH<sub>3</sub> and NH<sub>3</sub> are used in the reactant gas mixture. The flow rate ratio of PH<sub>3</sub> to NH<sub>3</sub> is  $0.75 \times 10^{-2}$  to 1. In this chemical vapor deposition process, the flow rate of silane is 1,000 sccm, the flow rate of NH<sub>3</sub> is 200 sccm, the flow rate of PH<sub>3</sub> is 1.5 sccm, the flow rate of H<sub>2</sub> is 1,000 sccm, the RF power used is 600 W, the pressure of the chamber is kept at 2.0 torr, the spacing between the electrodes is 962 mils (2.44 cm), the temperature of the susceptor is kept at 400°C, and a deposition rate of 197 nm/min is obtained. The physical properties of the films obtained are a tensile stress at  $1.3 \times 10^9$  dyne/cm<sup>2</sup> and a resistivity at  $9.6 \times 10^5$  ohm-cm. It is seen that by decreasing the flow rate of PH<sub>3</sub> relative to the flow rate of NH<sub>3</sub>, the resistivity of the film when compared to Example 4 is increased and the tensile stress is only slightly increased.

Example 6

In this example, both gases of  $\text{NH}_3$  and  $\text{PH}_3$  are used in the reactant gas mixture. The flow rate ratio of  $\text{PH}_3$  to  $\text{NH}_3$  is  $1.5 \times 10^{-2}$  to 1. In the chemical vapor deposition process, a flow rate of silane at 1,000 sccm is used, a flow rate of  $\text{PH}_3$  at 1.5 sccm is used, a flow rate of  $\text{NH}_3$  at 100 sccm is used, a flow rate of  $\text{H}_2$  at 1,000 sccm is used, an RF power of 600 W is used, a chamber pressure of 2.0 torr is used, a spacing between the electrodes of 962 mils (2.44 cm) is used, a susceptor temperature of  $400^\circ\text{C}$  is used, and a deposition rate of 240 nm/min is obtained. Amorphous silicon films having properties of a tensile stress at  $4.7 \times 10^9$  dyne/cm<sup>2</sup> and a resistivity at  $3.6 \times 10^5$  ohm-cm are obtained. It is seen in comparison to Example 5 that by decreasing the ammonia content in the reactant gas mixture as compared to that of  $\text{PH}_3$ , the resistivity of the deposited film is reduced and the tensile stress is slightly increased.

Example 7

In this example, both gases of  $\text{PH}_3$  and  $\text{NH}_3$  are used in the reactant gas mixture. The flow rate ratio of  $\text{PH}_3$  to  $\text{NH}_3$  is  $0.6 \times 10^{-2}$  to 1. It is believed that a flow rate ratio of  $\text{PH}_3:\text{NH}_3$  as low as  $0.1 \times 10^{-2}$  or 0.001:1 may be used. In the chemical vapor deposition process, the flow rate of silane is 1,000 sccm, the flow rate of  $\text{NH}_3$  is 200 sccm, the flow rate of  $\text{PH}_3$  is 1.5 sccm, the flow rate of  $\text{H}_2$  is 1,000 sccm, the RF power used is reduced to 400 W, the pressure of the chamber is kept at 2.0 torr, the spacing between the electrodes is 962 mils (2.44 cm), the temperature of the susceptor is kept at  $400^\circ\text{C}$ , and a deposition rate of 180 nm/min is obtained. The physical properties of the films obtained are a tensile stress at  $6.3 \times 10^9$  dyne/cm<sup>2</sup> and a resistivity at  $7.0 \times 10^6$  ohm-cm. It is seen that by increasing the flow rate of  $\text{NH}_3$  as compared to Example 6, the resistivity of the film is greatly increased while the tensile stress almost remained constant.

Example 8

In this example, both gases of  $\text{PH}_3$  and  $\text{NH}_3$  are used in the reactant gas mixture. The flow rate ratio of  $\text{PH}_3$  to  $\text{NH}_3$  is  $2.5 \times 10^{-2}$  to 1. It is believed that a flow rate ratio of  $\text{PH}_3:\text{NH}_3$  as high as  $1 \times 10^{-1}$  or 0.1:1 may be used. In the chemical

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vapor deposition process, the flow rate of silane is 1,000 sccm, the flow rate of  $\text{NH}_3$  is 100 sccm, the flow rate of  $\text{PH}_3$  is 2.5 sccm, the flow rate of  $\text{H}_2$  is 1,000 sccm, the RF power used is 400 W, the pressure of the chamber is kept at 2.0 torr, the spacing between the electrodes is 962 mils (2.44 cm), the temperature of the susceptor is kept at 400°C, and a deposition rate of 190 nm/min is obtained. The physical properties of the films obtained are a tensile stress at  $4.8 \times 10^9$  dyne/cm<sup>2</sup> and a resistivity at  $6.0 \times 10^4$  ohm-cm. It is seen that by increasing the flow rate of  $\text{PH}_3$  and comparing to Example 7, the resistivity of the film is greatly decreased while the tensile stress remains essentially constant.

#### Example 9

In Example 9, a doping gas of  $\text{PH}_3$  and a gaseous nitrogen  $\text{N}_2$  are used in a reactant gas mixture. The flow rate of silane is 1,000 sccm, the flow rate of  $\text{PH}_3$  is 2.5 sccm, the flow rate of  $\text{N}_2$  is 1,500 sccm, and the flow rate of  $\text{H}_2$  is 1,000 sccm. The RF power used is 600 W, the pressure of the chamber is 1.2 torr, the spacing of the electrodes is 962 mils (2.44 cm), the susceptor temperature is 400°C, and the deposition rate obtained is 190 nm/min. An amorphous silicon film having a desirable resistivity is obtained. The physical properties of the film are measured at a tensile stress of  $2.5 \times 10^9$  dyne/cm<sup>2</sup> and a resistivity of  $9.6 \times 10^5$  ohm-cm. As expected, increasing the concentration of nitrogen increases the resistivity and decreases the conductivity.

#### Example 10

In Example 10, a doping gas of  $\text{PH}_3$  and gaseous nitrogen  $\text{N}_2$  are used in the reactant gas mixture. The flow rate of silane is 1,000 sccm, the flow rate of  $\text{PH}_3$  is 2.5 sccm, the flow rate of  $\text{N}_2$  is 500 sccm, and the flow rate of  $\text{H}_2$  is 1,500 sccm. The RF power used is 600 W, the pressure of the chamber is 1.2 torr, the spacing of the electrodes is 962 mils (2.44 cm), the susceptor temperature is 400°C, and the deposition rate obtained is 194 nm/min. An amorphous silicon film having a desirable resistivity is obtained. The physical properties of the film are measured at a compressive stress of  $1.1 \times 10^9$  dyne/cm<sup>2</sup> and a resistivity of  $8.2 \times 10^2$  ohm-cm. The data is consistent with the results obtained on the other examples.

Examples 1 through 3 shown above are comparative examples prepared by prior art methods. Examples 4 through 10 shown above illustrate the advantages made possible by the present invention. The data for Examples 1 through 10 are shown below in Tables 1 and 2.

TABLE 1

	Example 1	Example 2	Example 3	Example 4	Example 5
<b>SiH<sub>4</sub></b> <b>sccm</b>	1000	1000	1000	1000	1000
<b>PH<sub>3</sub></b> <b>sccm</b>	--	5.5	--	2.5	1.5
<b>NH<sub>3</sub></b> <b>sccm</b>	--	--	500	200	200
<b>PH<sub>3</sub>/PH<sub>3</sub></b> <b>x10<sup>2</sup></b>	--	--	--	1.25	0.75
<b>H<sub>2</sub></b> <b>sccm</b>	1000	1000	1000	1000	1000
<b>power</b> <b>W</b>	300	300	300	600	600
<b>pressure</b> <b>torr</b>	2.0	2.0	2.0	2.0	2.0
<b>spacing</b> <b>mil</b>	962	962	962	962	962
<b>temp</b> <b>°C</b>	410	410	410	400	400
<b>dep rate</b> <b>nm/min</b>	168	156	135	197	197
<b>stress</b> <b>dyne/cm<sup>2</sup></b>	C 8.0E8	C 1.7E9	T 7.4E9	T 4.0E8	T 1.3E9
<b>resistivity</b> <b>ohm-cm</b>	2.0E9	1.7E2	2.2E10	1.6E5	9.6E5

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TABLE 2

	Example 6	Example 7	Example 8	Example 9	Example 10
<b>SiH<sub>4</sub></b> sccm	1000	1000	1000	1000	1000
<b>PH<sub>3</sub></b> sccm	1.5	1.5	2.5	2.5	2.5
<b>NH<sub>3</sub></b> sccm	100	250	100	--	--
<b>PH<sub>3</sub>/PH<sub>3</sub></b> <b>x10<sup>2</sup></b>	1.50	0.60	2.50	--	--
<b>N<sub>2</sub></b> sccm	--	--	--	1500	500
<b>H<sub>2</sub></b> sccm	1000	1000	1000	1000	1500
<b>power</b> <b>W</b>	600	400	400	600	600
<b>pressure</b> <b>torr</b>	2.0	2.0	2.0	1.2	1.2
<b>spacing</b> <b>mil</b>	962	962	962	962	962
<b>temp</b> <b>°C</b>	400	400	400	400	400
<b>dep rate</b> <b>nm/min</b>	240	180	190	190	194
<b>stress</b> <b>dyne/cm<sup>2</sup></b>	T 4.7E9	T 6.3E9	T 4.8E9	T 2.5E9	C 1.1E9
<b>resistivity</b> <b>ohm-cm</b>	3.6E5	7.0E6	6.0E4	9.0E5	8.2E2

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By mixing the doping gases of  $\text{PH}_3$  and  $\text{NH}_3$  together at various volume ratios, i.e. in the range between about 1000:1 and about 10:1 for  $\text{NH}_3:\text{PH}_3$ , amorphous silicon films having desirable stress values and resistivity values can be obtained. It is shown in Figure 3 that by changing the phosphine content in the reactant gas mixture, the conductivity of the films can be changed. For instance, increasing the phosphine content increases the conductivity of the film since phosphorus is an election donor. Similarly, changing the nitrogen content in the reactant gas mixture changes the resistivity of the film obtained since nitrogen contributes to the insulating property of the film. For instance, by increasing the nitrogen content of the reactant gas mixture, the resistivity of the amorphous silicon film obtained is increased. A desirable range for the resistivity of the present invention amorphous silicon based film is between about  $10^3$  and about  $10^7$  ohm-cm. This range is obtainable as shown by the data shown in Table 1 and other experimental data not presented here. A preferred range of resistivity is between about  $10^5$  and about  $10^6$  ohm-cm. Thus, by using the inventive reactant gas mixture of  $\text{PH}_3$  and  $\text{NH}_3$ , an amorphous silicon-based film with a controlled conductivity and low stress may be formed.

The stress level in the films is generally preferred to be minimized. The stress values should be kept in the low  $10^9$  dyne/cm<sup>2</sup> or in the high  $10^8$  dyne/cm<sup>2</sup> range. As seen in Figure 4, the stress level remains essentially constant with changing flow rate ratios of  $\text{PH}_3:\text{NH}_3$ . The novel method described herein enables a suitable control of the type of stress in the amorphous silicon film deposited while enabling a predictable selection of the resulting resistivity.

Examples 1 through 8 used ammonia as the nitrogen-containing gas. Examples 9 and 10 used gaseous nitrogen  $\text{N}_2$  as the nitrogen-containing gas and produced controllable resistivities in the range of  $10^2$  to  $10^4$  ohm-cm. It is believed that yet other nitrogen-containing gas such as  $\text{N}_2\text{O}$  would produce similar results. We believe that the nitrogen is introduced into the amorphous silicon matrix at levels far above those associated with doping levels. While increasing concentrations of the semiconductor n-type dopant P from the  $\text{PH}_3$  increases conductivities (decreases resistivities), increasing concentrations of nitrogen tend to increase the electronic band gap as the resultant material progressively changes from amorphous silicon to silicon nitride. The larger band gaps are associated with

increased resistivity. Thus, similar effects should be obtainable by use of carbon-containing or oxygen-containing gases which drive the material toward the semi-insulator silicon carbide and the dielectric silicon dioxide.

For example, a carbon-containing volatile (e.g., a gas or a gaseous substance) may be introduced during the deposition of an amorphous silicon-based film to control the conductivity of the deposited film. In one embodiment, methane ( $\text{CH}_4$ ) is introduced into the deposition chamber along with a silicon-containing volatile (e.g., silane gas) and a dopant volatile (e.g.,  $\text{PH}_3$  gas or  $\text{B}_2\text{H}_6$  gas) to form an amorphous silicon-based film. As shown in Figure 5, when phosphine gas is used as the dopant volatile, the resistivity of the deposited film increases as the flow rate of methane is increased relative to the flow rate of the phosphine gas (i.e., as the flow rate ratio  $\text{PH}_3:\text{CH}_4$  decreases). Thus, the addition of a carbon-containing volatile into the deposition chamber tends to increase the resistivity of the deposited film, assuming other factors remain unchanged. In another embodiment, a nitrogen-containing volatile (e.g.,  $\text{NH}_3$ ,  $\text{N}_2$ , or  $\text{N}_2\text{O}$ ) may be introduced into the deposition chamber along with a carbon-containing volatile (e.g.,  $\text{CH}_4$ ) and a dopant volatile (e.g.,  $\text{PH}_3$  or  $\text{B}_2\text{H}_6$ ). In this embodiment, the carbon-containing volatile and the nitrogen-containing volatile serve to increase the resistivity of the deposited film, and the dopant volatile serves to increase the conductivity of the deposited film. In any of these embodiments, the amorphous silicon-based film may be formed by many film forming techniques, including chemical vapor deposition (CVD), plasma enhanced chemical vapor deposition (PECVD), and physical vapor deposition (PVD) techniques. When the film is formed using PVD, the carbon-containing volatile may be introduced into the deposition chamber by RF sputtering a high-purity silicon carbide target.

The examples described above show an amorphous silicon film having a resistivity controllable in the range of  $10^2$  to  $10^7$  ohm-cm. We believe that the controllable range can be extended to  $10^{10}$  ohm-cm by using very limited amounts of phosphine, particularly with the heavy ammonia concentration of Example 3. The invention thus provides a method of controllably achieving resistivities in the range of  $10^3$  to  $10^9$  ohm-cm, which were not easily obtainable in the prior art.

While the present invention has been described in an illustrative manner, it

should be understood that the terminology used is intended to be in a nature of words of description rather than of limitation.

Furthermore, while the present invention has been described in terms of a preferred embodiment thereof, it is to be appreciated that those skilled in the art will readily apply these teachings to other possible variations of the invention. For instance, other volume ratios between the doping gases may be suitably used in place of those shown in the examples. The dopant gas  $\text{PH}_3$  of the examples provides n-type doping. Other n-type dopant gases may be used with the invention. Also, p-type dopant gases, such as  $\text{B}_2\text{H}_6$ , may be used with the invention. The hydrogen gas of the examples is less reducing than  $\text{NH}_3$  and thus acts primarily as a carrier gas although it is conventional to use hydrogen to deposit high-quality amorphous silicon. Other carrier gases that are less reducing than the nitrogen-containing gas can be substituted for the  $\text{H}_2$ . Examples of such carrier gases are Ar and He. Furthermore, even though the process of PECVD is used to deposit layers in a field emission display device, other processes such as CVD may also be used to deposit amorphous silicon based films that have controlled conductivity in other semiconductor devices.

Other embodiments are within the scope of the claims.

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